Moderated and Fast Neutrons Dosimetry Using Radiometric Gafchromic™ EBT3 Film

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Presentation scheme

- Introductory remarks
  - Open problems in neutron dosimetry (does not include hidden slides)
  - Neutron detection approaches
- Experiment on EBT3
  - The material
  - The irradiation facilities @ ENPS-NRC-EAEA
- The results
  - Scanning and color levels
  - Correlation scheme between interaction
  - Conversion coefficient
  - Atomic displacement
  - **Understanding non-linearity**
  - **Absorption spectroscopy**
- Concluding remarks

Problems in Neutron dosimetry

Perturbation of neutron fluence

Scattering, Absorption, Reflection	Change in energy spectrum

Non-linearity of dosimeter itself

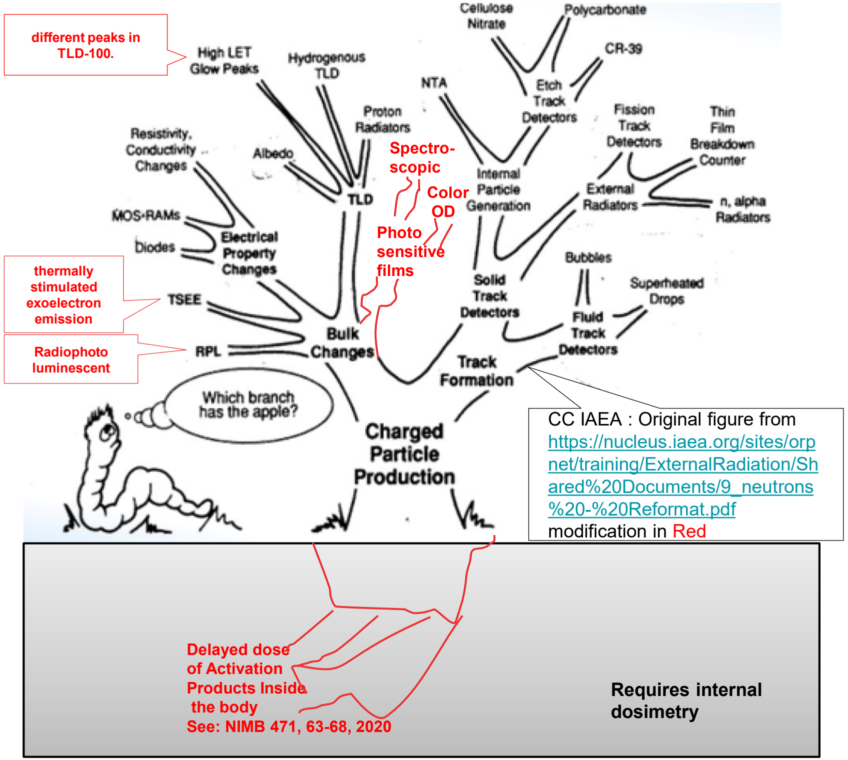
Temporal response nonlinearity over time of exposure	nonlinear fluence to dose conversion

Other factors include **Uncertainty and bias**

Interference with other type of radiation	**Similarity in neutron energy spectrum of the source**	**Type of dosimeter (and its response)**

Dose calibration approach

- Reference calibration labs uses the ***radionuclide neutron sources (AmBe and Cf)*** in accordance with ISO 8529 & IEC 61005.
- Usually, the calibration factor of an area monitor **must be independent of the conditions prevailing in the measurement** setup, i.e. it is to be determined for a free-field fluence rate in vacuum.
- Avoid accompanied scattered radiation component which has to be corrected for using a suitable method.
- The **measurand is the neutron fluence (or fluence rate) convertible** to ambient dose equivalent H*(10).
    - Earlier, we made such calibration using CR-39 PADC, however, CR-39 requires very large fluence to induce an effect < 10^16 n/cm2 or 1MGy (suitable for high dose measurements) Refs. ***NIMA 949 (2020) 162889, ARI 176 (2021) 109872, NIMB 461 (2019) 210–218, JNRD 14 (2017) 41-46.***



Work on EBT3

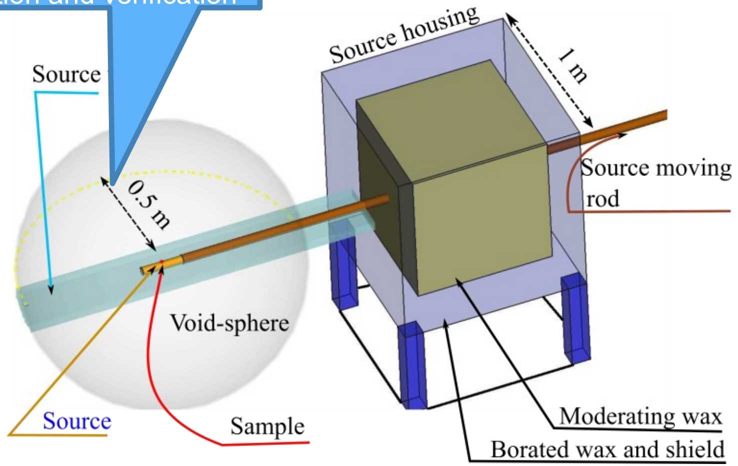
- General dosimetry function
  - EBT-3 is a radiochromic film: designed for self-developing feature
  - EBT-3 is designed for High LET radiation (>10 keV/µm:), e.g. electrons and high energy charged particles
  - Its response to photon is due to High-LET secondary electrons
  - EBT-3 chemical composition is based on active component of $C_{25}H_{41}\mathbf{Li}O_2$
  - **EBT-3 has Long-Term Stability (not permanent)**
  - Technically, not designed for neutrons
    - Claimed to have low sensitivity
    - Claimed to have response depending on energy

- Specifics adaptation for current work
  - **The neutron's interaction with the active layer depends on two phenomena, i.e.**
    - **the atomic displacement and**
    - **lithium (n,alpha) reaction**
  - **The atomic displacement induces high energy proton and ions**
  - **Li-6(n,alpha) reaction is induced by thermal and moderated neutrons (these are 2 charged particles one of which is also beta emitter)**
  - **Both phenomenon shall deposit energy in the film through High-LET radiation**

Irradiation facilities @ ENPD-NRC-EAEA

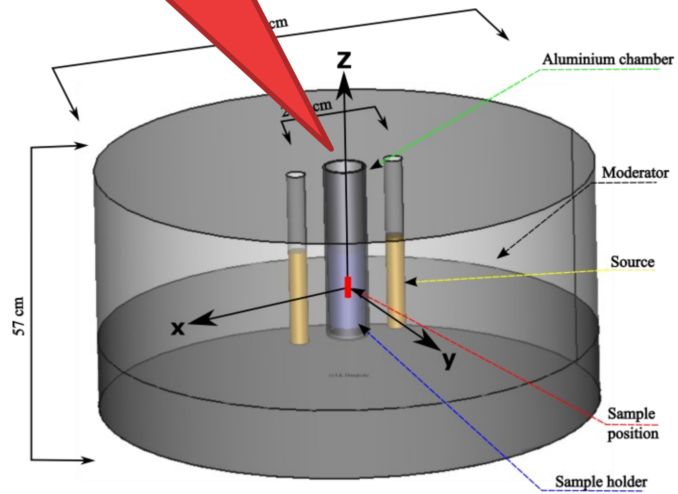
Fast neutron

Intended for methods validation and verification



Intended for neutron activation analysis

Moderated Neutron



Fluence rate: (1.2± 0.1)×10^5 n/cm^2 s

Determined by activation techniques

Ref. Phys. Scr. 96 (2021) 045304 and citations therein

https://doi.org/10.1088/1402-4896/abe258

Activity: 2×5 Ci

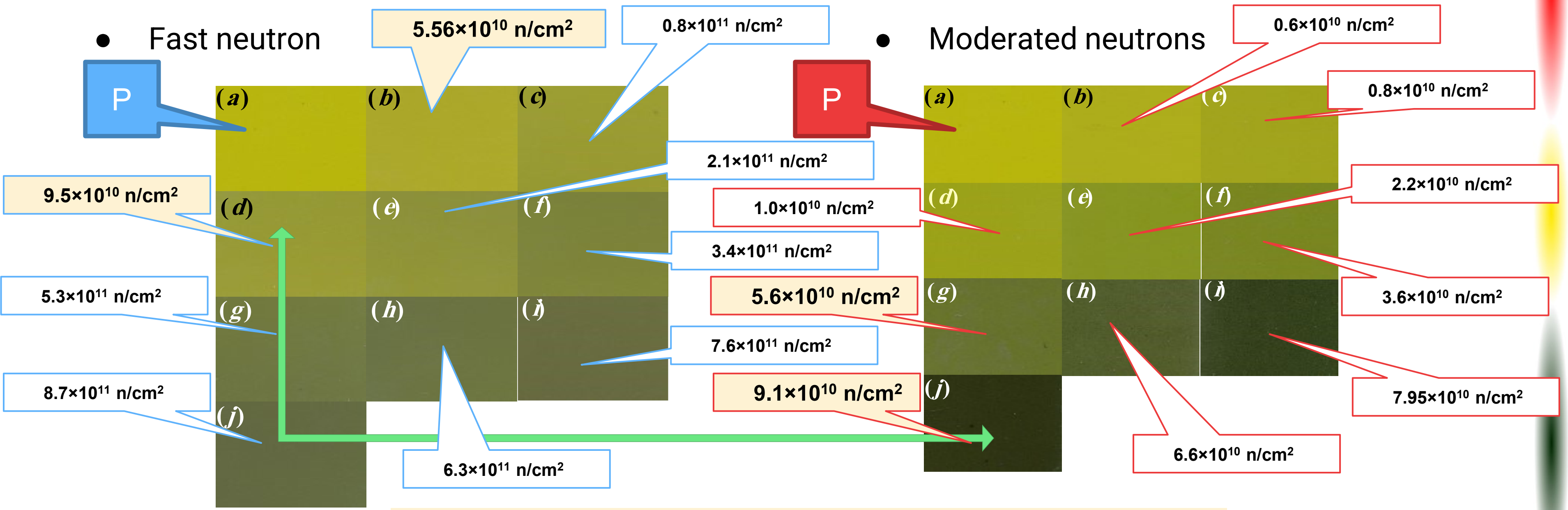
Fluence rate: (2.3± 0.2)×10^4 n/cm^2 s thermal

Ref: Phys. Scr. 94(1) (2019) 015301 and citations therein

https://doi.org/10.1088/1402-4896/aaecb0

Scans

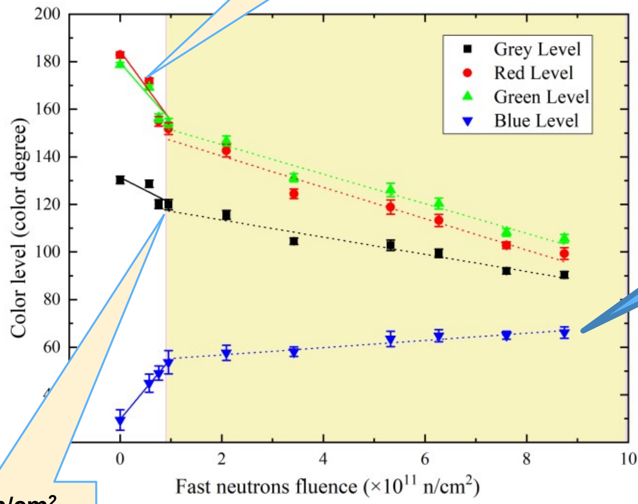
- Fast neutron
- Moderated neutrons



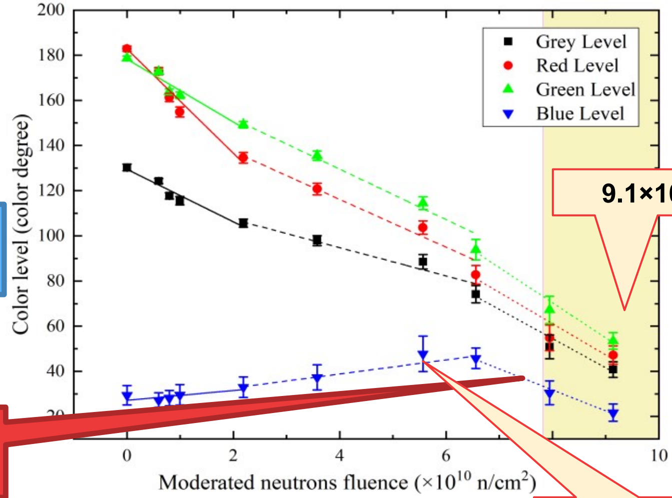
Yellow bubble boxes points to samples irradiated with same fluences but in different setups

Color level

- Fast neutron



- Moderated neutrons



Conversion coefficients for Ambient Dose Equivalent

- The known neutron dose conversion coefficients for Ambient Dose Equivalent, H*(10) is usually higher for high energy neutrons.
- This only account for direct biological effect of neutron due to displacement of atoms upon recoil.
- **This disregard the effect of prompt, delayed neutron activation products and bremsstrahlung radiation**

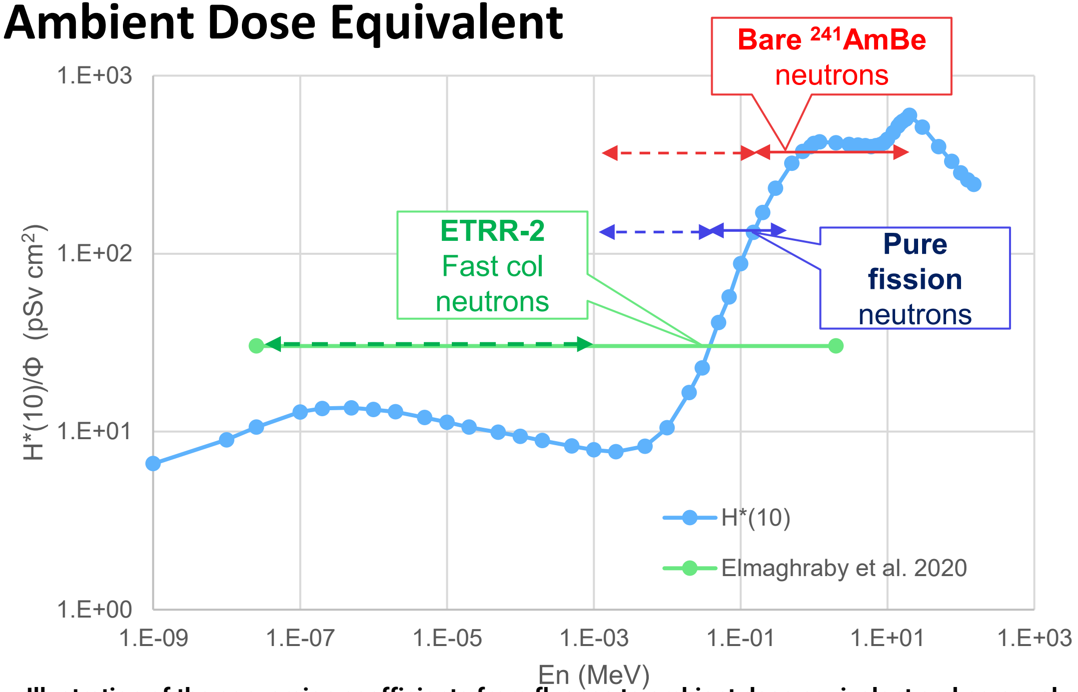


Illustration of the conversion coefficients from fluence to ambient dose equivalent and personal dose equivalent for monoenergetic neutron H*(10)/Φ (without other neutron interactions)

***Green Horizontal line** is ETRR-2 spectrum averaged value, Ref. NIMA 949 (2020) 162889*

***Red Horizontal line** for expected value of Bare AmBe neutrons*

***Blue Horizontal line** for expected value with reference to Watt distribution*

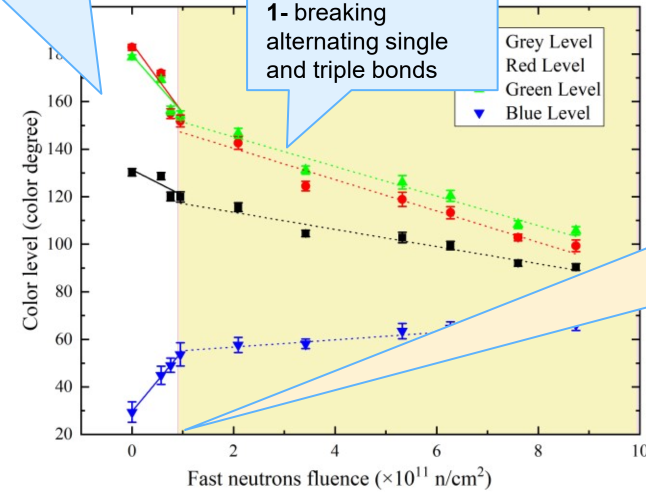
- - - - - - - - - -Dashed lines for uncertain energy domain suitable for dosimetry

Color level (Understanding Non-linearity)

Two mechanisms
1- breaking alternating single and triple bonds
2- cross-polymerization reaction

- Fast neutron

single mechanism
1- breaking alternating single and triple bonds

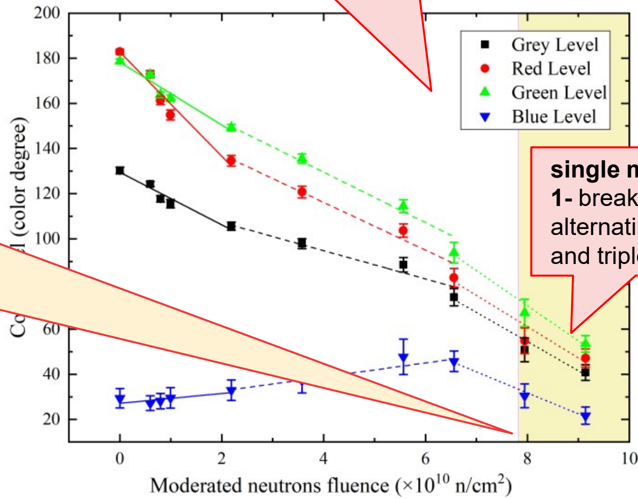


It depends on fluence not the energy. So it is related to no. od dpa

Point of dominance of one interaction regeme of energy deposition over others around 6.7×10^{10} n/cm^2

- Moderated neutrons

Two mechanisms
1- breaking alternating single and triple bonds
2- cross-polymerization reaction



single mechanism
1- breaking alternating single and triple bonds

The extent of the response may be affected depending on the availability of the interaction sites. Once a specific site is depleted, the overall effect follows the response is driven by other mechanism(s).

Atomic displacement

- Based on our previous Gaussian model for multiple atomic displacements model [ref*] , the expected percentage of recoil atoms, regardless of energy are as in the table

  Ref*: NIMB 398 (2017) 42–47
  https://doi.org/10.1016/j.nimb.2017.03.054.

- Displaced hydrogen atoms could bond again with the displaced oxygen atoms to form OH_2, with carbon atoms to form lower molecular mass hydrocarbon
- *Thermal and moderated neutrons, having energy less than the lattice barrier and/or chemical bond energy, cannot, in principle, induce atomic displacement.*

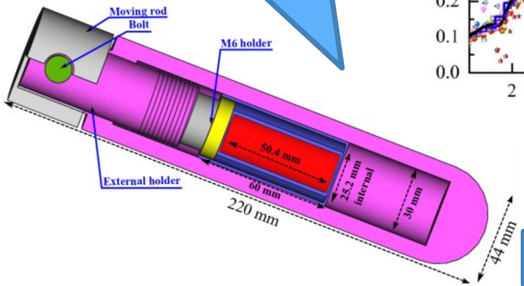
Recoil atom	Displacement energies (av.)	Precent of total atoms
H	4.2 to 5.5 eV av. 5 eV	**~67%**
C	4.1 to 7.7 eV av. 6.5 eV	**~21.2%**
O	5.16 to 5.46 eV av. 5.46	**10.6%**
Al	Av. 7 eV	0.9%
Li	Av. 5 eV	0.3%

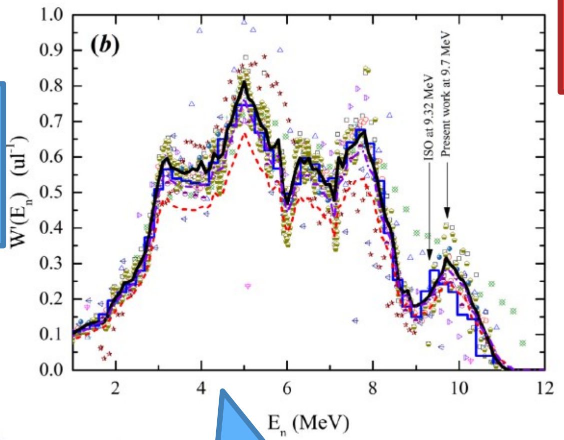
Recovery of displacement can occur during the curing time of the active layer; however, the number of survived defects may still be proportional to the number of primary displaced atoms.

Effect of Irradiation facilities @ ENPD-NRC-EAEA

Fast neutron

Gammas are negligible
Thermal neutrons are hindered
Stable flux
unidirectional fluence
H*(10)/Φ ~~ 400 pSv cm²

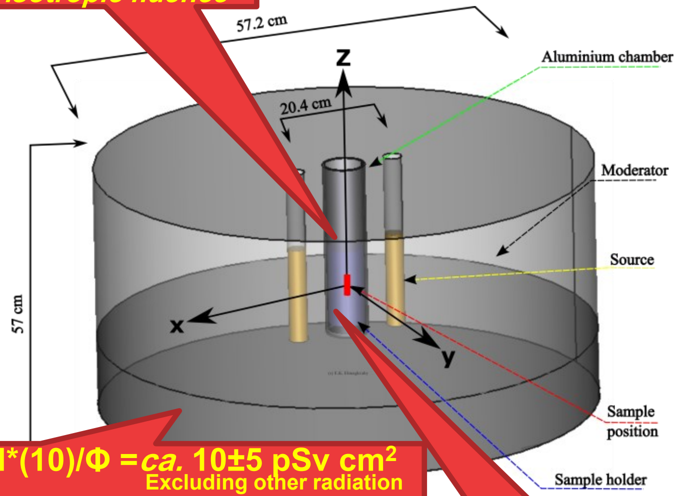




H*(10)/Φ =*ca.* 400±50 pSv cm²

Include all of
Thermal, epithermal, and fast neutrons
Stable isotropic fluence

Moderated Neutron



H*(10)/Φ =*ca.* 10±5 pSv cm²
Excluding other radiation

Existing all of
Prompt gammas
Bremsstrahlung
Delayed gammas

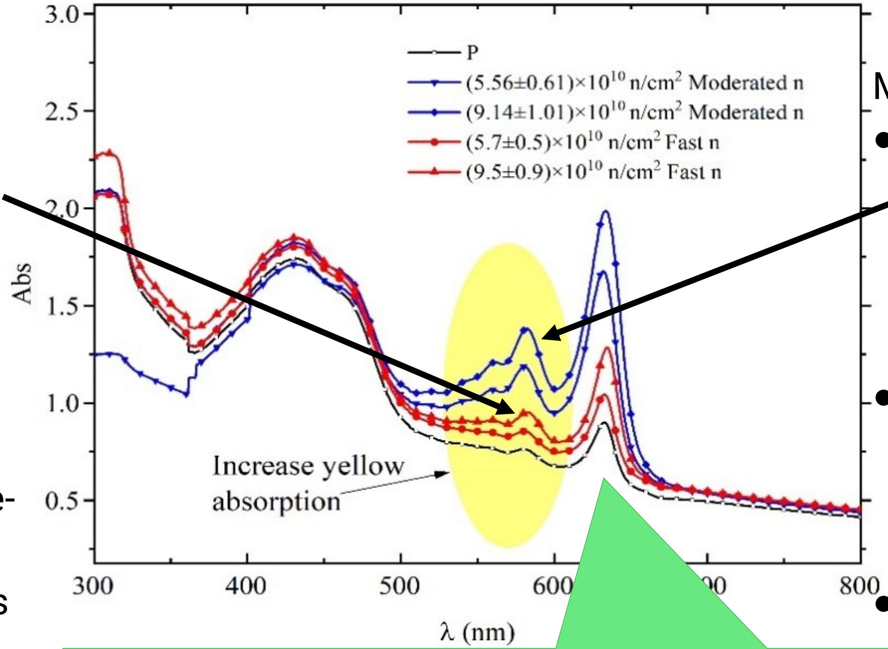
Activity : 5 Ci
Flux: $(1.1 \pm 0.1)\times10^7$ n/s (this is yield in physics terms)
Ref. NIMA 942 (2019) 162387.
https://doi.org/10.1016/j.nima.2019.162387

Activity: 2×5 Ci
Fluence rate: $(2.3\pm 0.2)\times10^4$ n/cm² s thermal
Ref: Phys. Scr. 94(1) (2019) 015301 and citation
https://doi.org/10.1088/1402-4896/aaecb0

Source of dissimilarity (absorption spectroscopy)

Fast neutrons

- Both the red peak (635 nm) and the yellow peaks (560 nm and 582 nm) increase with the same proportion (approximately).
- This is why the blue-channel in the diametric measures continues to increase (relatively).



The red absorption peak around 632 nm increases continuously with fluence, which is why the corresponding red and grey channels in the dosimetric measurements decrease with fluence.

Moderated neutrons

- The yellow peak absorptions (560 nm and 582 nm) increase more rapidly than the red peak (632 nm).
- Dissimilarity is due to difference between gamma and neutron interaction
- This is why the blue-channel in the photometric measures decrease with fluence.

Concluding remarks

The present preliminary results showed that:

- dependence of the workplace usage limits the validation, verification and calibration of the EBT3 film for neutron dosimetry.
- The spectroscopic techniques or the color level separation could, in principle, separate the dependence of neutron energy based on the proportion of the yellow peak absorptions (560 nm and 582 nm) or its counterpart blue level.
- The existence of two dynamic ranges was evidence of the existence of multiple interaction mechanisms that develop color centers (chromophores) in the active layer below **6.7×10^{10} n/cm^2**.
  - cross-polymerization reaction.
  - bond breakdown.

Some of the current data and more additional could be found in Science Research Network (**SSRN) preprint repository** at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4168071

Thank you